551.521.31(048)

SECTION I.—AEROLOGY.

ATMOSPHERIC TRANSPARENCY FOR RADIATION.[1]

By F. E. FOWLE.

[Read Feb. 14, 1914, before the Philosophical Society of Washington, D. C.

A comparison of the transparency of the earth's atmosphere as determined by different observers at various altitudes with values derived by computation from the barometric height, the amount of aqueous vapor, and the transparency above Mount Wilson for dry air will be made in this communication.

OBSERVED TRANSPARENCIES.

For observed transparencies of the air recent data from the following stations will be used: Mount Whitney, altitude 4,420 meters (1); Alta Vista, 3,260 meters (2); Pedrogil, 1,950 meters (2); Mount Wilson, 1,730 meters (1); Bassour, 1,160 meters (1); Orotava, 100 meters (2); Potsdam, 90 meters (2); Upsala, 50 meters (3); and Washington, 10 meters. The mean values for Washington were recomputed from the values given in volume 2 of the Annals of the Astrophysical Observatory of the Smithsonian Institution, omitting those dates when the transparency was apparently affected by volcanic dust. All the data for the other places were obtained during times probably free from such disturbance. The data will be found collected in Table 2.

COMPUTED TRANSPARENCIES.

In the solar-constant work at Mount Wilson (4) coefficients of atmospheric transmission have been obtained at numerous wave lengths between 0.34μ and 2.5μ. It has been shown in an earlier communication (5) that these coefficients vary from day to day according to the amount of water vapor present in the atmosphere. The total quantity of atmospheric moisture present between the observing station and the limit of the atmosphere was measured by the spectroscopic method described in a yet earlier communication (6). The atmospheric moisture ranged from 0.27 to 1.77 centimeters of precipitable water, representing observations of 180 days. Coefficients of transmission for the dry air above Mount Wilson were derived for 30 different wave lengths from those observed for moist air by the following process: The logarithms of the observed transmission coefficients were plotted as ordinates against the corresponding quantities of precipitable atmospheric moisture as abscissæ, and the best representative curves (which appeared to be right lines) were produced by a short extrapolation to zero of moisture. From consideration of the slope of these right lines, factors expressing the effect of water vapor on the atmospheric transmission were determined for the 30 wave lengths mentioned. The process and results are given in more detail in the paper cited (6), from which is taken the following table:

[1] Published by permission of the Secretary of the Smithsonian Institution.

TABLE 1.—*Transmissibility of radiation through the air above Mount Wilson.*

Wave lengths.	$0\mu.370$	$0\mu.400$	$0\mu.430$	$0\mu.460$	$0\mu.500$	$0\mu.600$	$0\mu.750$	$1\mu.000$	$1\mu.500$
$a_{a\lambda}$	0.683	0.757	0.808	0.851	[1]0.885	[1]0.916	0.977	0.987	0.990
$a_{a\lambda}$ (theoretical)	.680	.755	.808	.850	[1].890	[1].946	.977	.987	.986
$a_{w\lambda}$	.957	.962	.967	.971	.976	.977	.988	.990	.988

[1] Places of selective transmission.

The first line of the table contains $a_{a\lambda}$, the derived coefficient of transmission for dry air above Mount Wilson. The second line contains the corresponding coefficients as derived by Rayleigh's theory from the number of molecules in the air. The third line will be described below. In the formula $I_{m\lambda} = I_{o\lambda}(a_{a\lambda})^m$, if $I_{o\lambda}$ is the intensity of the incident beam of wave-length λ, then $I_{m\lambda}$ would be its intensity after passing through the mass of dry air m where m is unity for a celestial body observed in the zenith and is approximately (within 1%) equal to the secant of the zenith distance when the body is more than 20° above the horizon.

The theory and theoretical limitations of the method employed for determining the atmospheric transmission coefficients were given in volume 2 of the Annals of this Observatory, pages 13 to 17. The soundness of the method is confirmed by a comparison of the derived coefficients for dry air with those computed from Lord Rayleigh's theory of the atmospheric scattering of light: First, because, assuming that the depletion of energy is due wholly to scattering by the molecules of the components of dry air, the number of molecules per cubic centimeter of a gas (760 millimeters pressure, 0° C.), 26 billion-billion, determined through the transmission coefficients, corresponds very closely with what is perhaps the best figure, 27 billion-billion, as determined by other processes (7); second, because of the continued agreement of the computed and observed values over more than two octaves, except in the region of selective absorption near the D lines ($\lambda = 0.53\mu$ to $\lambda = 0.65\mu$), this agreement indicating a variation inversely as the fourth power of the wave length as would be expected from Rayleigh's theory of molecular scattering.

The third line of the table gives correction factors by which the dry-air transmission coefficients must be multiplied when the air vertically above the place contains an amount of water vapor which if condensed would form a layer 1 centimeter thick (1 centimeter precipitable water). The transmission coefficient for moist air vertically above Mount Wilson would then be $a_{a\lambda}\,(a_{w\lambda})^d$, where d is the amount of precipitable water in centimeters in the atmosphere vertically above. The quantity d is best determined spectroscopically (8) but in the absence of such determinations Hann's formula $d = ke$ may be used where e is the vapor pressure in centimeters and k a constant for the place and equal to about 1.9 for Mount Wilson. The writer showed (9) that whereas redetermination by spectroscopic observations gave a mean value of $k=1.8$ above Mount Wilson, that agreed approximately with the value of Hann's formula, yet for individual days k ranged from 0.33 to 5.20; accordingly little reliance should be placed upon this formula except when mean values for many days are under consideration.

While $a_{a\lambda}$, due to dry air, agrees very nearly with what would be expected from molecular scattering, $a_{w\lambda}$, due to water vapor, is much smaller than would be expected from a consideration of the number of molecules of water vapor present in the atmosphere and does not vary so closely with the inverse fourth power of the wave length. It behaves as if it expressed a scattering due to grosser particles which would deplete more uniformly than molecules throughout the spectrum. This possibly may indicate the association of dust with the water vapor, but perhaps more probably the formation of ions or nuclei under the influence of the ultra-violet radiation from the sun.

The more general formula for the transmission by moist air at any altitude, where the barometer is β centimeters when the amount of precipitable water is d centimeters and for any zenith distance of which m is the secant, is—

$$(a_{a\lambda})^{m\beta/62}(a_{w\lambda})^{dm} \quad \text{..........} \quad (A)$$

This formula has no factor allowing for the presence of dust and so is applicable only where the altitude renders the air comparatively free from dust. When the amount of aqueous vapor in the atmosphere is not known by spectroscopic or other exact methods, recourse must be had to Hann's expression, which, for any altitude, may be expressed as—

$$2.3\ e\ 10^{\frac{-h}{23000}}$$

where e is the vapor pressure in centimeters at the place and h the altitude in meters above sea level. As before stated, this, on the average, may give values approximately correct, although values for individual days may be several times too large or small. The use of formula A is as follows: Suppose 0.808 ($=a_{a\lambda}$) of the light at 0.431μ coming from a celestial body in the zenith, $m=1$, reaches an observer on Mount Wilson, where the barometer equals 62 centimeters and when the air is void of water vapor; and suppose, furthermore, that 0.967 ($=a_{w\lambda}$) of the remaining light would be transmitted were it to pass through 1 centimeter of water in the form of vapor. Then at any other place, for example, Alta Vista, where the barometer reads 50.9 centimeters and the precipitable water is 0.21 centimeter for $m=1$, the corresponding transmission is—

$$(0.808^{509/620}) \times (0.967^{0.21/1.00}) = 0.840 \times 0.993$$
$$= 0.834$$

TABLE 2.—*Observed and computed atmospheric transmission coefficients.*

Wave length	μ 0.360	μ 0.431	μ 0.452	μ 0.475	μ 0.503	μ 0.574	μ 0.600	μ 0.624	μ 0.653	μ 0.686	μ 0.720	μ 0.986	μ 1.74
$a_{a\lambda}$	(.660)	.808	.840	.863	.885	.905	.913	.929	.938	.959	.970	.986	.990
$a_{w\lambda}$	.950	.967	.967	.973	.977	.974	.977	.978	.985	.987	.988	.990	.990
Mount Whitney, 4,420 meters:													
Dry air	.741	.857	.883	.900	.916	.931	.938	.948	.955	.970	.980	.991	.993
Moist air	.738	.855	.881	.898	.914	.929	.936	.946	.954	.970	.980	.991	.993
Observed	.741	.845	.872	.904	.920	.932	.940	.948	.955	.962	.969	.975	.956
Departures [1]	−.004	.012	.010	−.007	−.007	−.003	−.004	−.002	−.001	.008	.011	.016	.037
Alta Vista, 3,260 meters:													
Dry air	....	.840	.867	.887	.901	.920	.929	.942	.948	.966	.975	....	....
Moist air	....	.834	.861	.882	.899	.914	.924	.937	.946	.963	.972	....	....
Observed	....	.822	.850	.872	.888	.904	.910	.922	.941	.958	.965	....	....
Departures [1]	....	.013	.012	.011	.012	.011	.015	.016	.005	.005	.007	....	....
Pedrogil, 1,950 meters:													
Dry air	....	.815	.845	.869	.889	.908	.916	.931	.940	.962	.971	....	....
Moist air	....	.799	.828	.853	.876	.893	.902	.918	.931	.953	.964	....	....
Observed	....	.800	.823	.846	.869	.885	.909	.910	.922	.932	.939	....	....
Departures [1]	....	−.001	.006	.008	.008	.009	−.008	.009	.010	.022	.026	....	....
Bassour, 1,160 meters:													
Dry air	.643	.796	.830	.855	.877	.910	.908	.925	.933	.957	.968	.984	.989
Moist air	.606	.766	.798	.828	.853	.883	.883	.900	.916	.942	.954	.970	.978
Observed	.601	.738	.769	.805	.836	.868	.879	.889	.908	.926	.937	.967	.976
Departures [1]	.008	.036	.036	.028	.020	.017	.004	.001	.009	.017	.018	.003	.002
Orotava, 100 meters:													
Dry air	....	.815	.845	.869	.889	.908	.916	.931	.940	.962	.971	....	....
Moist air	....	.706	.743	.778	.811	.827	.841	.863	.890	.919	.935	....	....
Observed	....	.666	.699	.727	.754	.776	.786	.801	.818	.837	(.850)	....	....
Departures [1]	....	.057	.059	.066	.070	.062	.064	.072	.081	.089	.091	....	....
Potsdam, 90 meters:													
Dry air	....	.769	.809	.834	.861	.885	.893	.914	.925	.951	.964	....	....
Moist air	....	.714	.750	.786	.819	.835	.849	.871	.895	.922	.940	....	....
Observed	....	.702	.726	.752	.777	.806	.828	.840	.851	.861	(868)	....	....
Departures [1]	....	.017	.032	.043	.051	.034	.025	.036	.049	.066	.077	....	....
Upsala, 50 meters:													
Dry air	....	....	.809	.834	.861	.885	.893	.914	.925	.951	.964	.982	.989
Moist air	....	....	.774	.806	.836	.857	.866	.889	.908	.936	.950	.968	.975
Observed	....	....	(.757)	(.772)	.791	.824	.834	.848	.869	.889	.900	.939	.942
Departures [1]	....	....	.022	.042	.054	.038	.037	.046	.043	.050	.052	.030	.034
Washington, 10 meters:													
Dry air	....	.769	.809	.834	.861	.885	.893	.914	.925	.951	.964	.982	.989
Moist air	....	.729	.767	.798	.830	.849	.861	.883	.904	.932	.947	.961	.973
Observed	....	.629	.664	.706	.735	.769	.784	.802	.828	.853	.865	.918	.930
Departures [1]	....	.137	.134	.115	.114	.094	.089	.092	.084	.085	.087	.050	.045
Washington, Feb. 15, 1907:													
Moist air	....	.760	.798	.826	.854	.877	.886	.907	.920	.946	.960	.979	.986
Observed	....	.735	.769	.834	.837	.850	.870	.875	.900	.910	.910	.955	.948
Departures [1]	....	.033	.036	.010	.020	.031	.018	.035	.021	.038	.052	.025	.039

Place.	Mount Whitney.	Alta Vista.	Pedrogil.	Bassour.	Orotava.	Potsdam.	Upsala.	Washington.	Washington, Feb. 15, 1907.
	Cm.	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*	*Cm.*
Precipitated H_2O	0.08	0.21	0.64	1.20	2.57	2.21	1.26	1.57	0.33
Barometer	44.7	50.9	59.5	66.0	75.9	76.0	76.0	76.0	76.0
Mean departure	.005	.011	.009	.015	.071	.043	.041	.091	.036

[1] Fractional departures of the observed from the computed values.

In Table 2 will be found, in 4-line groups, the comparisons for each station for a number of wave lengths. The first line of each group gives the transmissions computed from that for the dry air above Mount Wilson, taking into account only the difference of barometric pressure ($a_{a\lambda}^{\beta/620}$). They therefore represent the transmissions if no aqueous vapor were present. In the next line, these values have been multiplied by the correction factors for the mean amount of aqueous vapor present at each station ($a_{a\lambda}^{\beta/620}\, a_{w\lambda}^{d}$). These mean amounts of aqueous vapor together with the barometer heights are given at the foot of the table. The third line of each group gives the mean observed values. The fourth line, the fractional departure of the observed from the computed values. The average of these departures for all wave lengths for the various places is given in the last line at the bottom of Table 2.

CONCLUSIONS.

From Table 2 the following inferences may be made: The transparency of the air at any place depends on three factors: The transparency of dry air itself, which depends upon molecular scattering; the scatterings due to what may be termed wet haziness; and the scatterings due to dry haziness—the former associated with water vapor, the latter with dust. It is because of these associated disturbances, modifying the quality of the air with changing altitude at every wave length, that Bouguer's formula $a^{m\beta/760}$ for the transparency of the air can not be used in passing from one altitude to another. (In this formula a is the transparency at the surface of the earth, β the barometric pressure in millimeters, and m the air mass.)

For those stations where dry haziness is present the formula developed in this communication can not be expected to hold. The fractional departures given in the fourth line of Table 2 may however be taken as the vertical absorption coefficients due to this dust. For Orotava these average 7 per cent; for Potsdam, Upsala, and for Washington, on February 15, 1907, about 4 per cent. The data indicate that, as would be expected, the dust absorption does not vary much with the wave length (10).

At an altitude of about 1,000 meters the disturbance due to dry haziness may disappear and then formula (A) can be used to compute the transparency on clear days with an accuracy of about 1 per cent.

At Bassour (1,160 meters) the correction to the dry air transparency because of the aqueous vapor present varies with increasing wave lengths from 6 to 1 per cent.

At the altitude of Mount Whitney (4,420 meters) water vapor has practically disappeared, and the scattering of radiation on clear days is due almost wholly to the molecules of the air alone.

Certain writers have criticized the method now almost universally used in the determination of the atmospheric transmission, implying that even at Mount Wilson and at Mount Whitney our estimations are 50 to 100 per cent in error. It would seem a strange freak of chance that the values of the solar constant of radiation, derived from measures of the intensity of the sun's radiation at altitudes of 4,420, 1,730, and 1,160 meters, corrected for the corresponding atmospheric losses, should agree within 1 or 2 per cent if the method of finding the coefficients of atmospheric transmission were likely to produce values so grossly in error. Added evidence of the correctness of the estimation of the atmospheric losses is furnished:

1. By the fact that the losses in dry air vary as the inverse fourth power of the wave length, over a range of wave lengths from 0.36μ to 1.74μ except where selective absorption exists;
2. By the agreement between computations of the number of molecules present in the atmosphere based on transmission coefficients and those by the most approved laboratory methods;
3. By the agreement (when dust becomes a negligible factor) between values obtained by observation at Mount Whitney, Alta Vista, Pedrogil, and Bassour and those computed for these stations from values observed at Mount Wilson.

Before concluding, the writer wishes to express his gratitude to Mr. C. G. Abbot for his criticisms and suggestions in the course of the preparation of this matter for publication.

SUMMARY.

The transparency of the atmosphere on clear days is dependent on scattering due to three obstructions: The molecules of the air itself (dry air), hindrances associated with water vapor (wet haze), and ordinary dust (dry haze). It is due to the change in these last two factors with the altitude that the quality of the transparency of the air, even with homogeneous rays, changes and that Bouguer's formula for atmospheric transmission may not be used in passing from one altitude to another. These objections do not hold against its proper use with high and low sun observations at a single station.

Above an altitude of 1,000 meters on clear days the dry haze may become a negligible factor and the formula (A) developed in this communication can be used to compute the transparency to within 1 per cent.

Above Mount Whitney (4,420 meters) the wet haze on clear days may also become negligible and the obstruction offered to transmitted radiation is practically wholly due to the molecules of the air.

REFERENCES AND NOTES.

(1) Abbot, Fowle & Aldrich, Annals of the Astrophysical Observatory, Smithsonian Institution, v. 3, 1913.

(2) Müller, G. Die Extinction des Lichtes in der Atmosphäre. (Astrophysikalische Observatorium zu Potsdam, Publikationen, No. 64, 1912.)

(3) Lindholm, Extinction des radiations solaires dans l'atmosphère terrestre. Nova acta, R. soc. scient. Upsaliensis, ser. 4, v. 3, No. 6, 1913.

(4) Annals, Astrophysical observatory, Smithsonian Institution, v. 3, p. 138.

(5) Astrophysical journal, 1913, v. 38, p. 392.

(6) Astrophysical journal, 1912, v. 35, p. 149; 1913, v. 37, p. 359.

(7) Millikan, Physical review, ser. 2, 1913, v. 2, p. 109.

(8) Astrophysical journal, 1912, v. 35, p. 149.

(9) Astrophysical journal, 1913, v. 37, p. 359.

(10) The general mean for Washington shows a decided decrease of the fractional departures with increasing wave-length, the values approaching about 4 per cent in the infra-red on the clearest day. This variation may be due to insufficient allowance for water vapor. No spectroscopic determinations of the water vapor were available, and except at Mount Whitney, Mount Wilson, and Bassour, Hann's formula was used to estimate the amount.